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ISOTOPIC ABUNDANCES OF MAGNESIUM IN FIVE G AND K DWARFS

JOCELYN TOMKIN AND DAVID L. LAMBERT
McDonald Observatory and Department of Astronomy, University of Texas
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ABSTRACT

High-resolution low-noise Reticon observations of MgH lines in the spectra of μ Cas, ϵ Eri, 61 Cyg A and B, and Gmb 1830 have been analyzed by spectrum synthesis. The mixtures of the isotopes in μ Cas, ϵ Eri, and 61 Cyg A and B are not significantly different from the terrestrial mixture (^{24}Mg:^{25}Mg:^{26}Mg = 79:10:11). The estimated errors are such that limits for any enrichment or deficiency of ^{25}Mg and ^{26}Mg are ^{24}Mg:^{25}Mg:^{26}Mg = 74:13:13 to 86:7:7.

A nonterrestrial mixture—^{24}Mg:^{25}Mg:^{26}Mg = 94:3:3—is found in Gmb 1830. The accuracy of this result is such that approximate upper limits to the abundances of ^{25}Mg and ^{26}Mg are ^{24}Mg:^{25}Mg:^{26}Mg = 88:7:5. Although it is difficult to estimate lower error limits to the ^{25}Mg and ^{26}Mg abundances, it is clear that ^{26}Mg is present. The ^{25}Mg detection is marginal. Weak atomic lines of Na, Mg, and Al have been used to determine the abundances of these elements in Gmb 1830. The abundances of Na and Al relative to Mg are 0.6 $\pm$ 0.1 dex and 0.2 $\pm$ 0.1 dex, respectively, less than in the solar abundance distribution. (Na and Al each have only one stable isotope—^{23}Na and ^{27}Al—so that these are also the abundances of ^{23}Na and ^{27}Al relative to ^{24}Mg.)

The underabundances of the neutron-rich nuclei ^{23}Na, ^{25}Mg, ^{26}Mg, and ^{27}Al relative to the α-particle nucleus ^{24}Mg in Gmb 1830, which is an old, metal-deficient ([Fe/H] = -1.37) star, indicate that this was a characteristic of the composition of the Galaxy when Gmb 1830 formed. The theory of stellar nucleosynthesis of the heavy elements predicts that the composition of the early Galaxy could have shown exactly this effect. In other words, the abundances of Gmb 1830 are observational evidence in support of stellar nucleosynthesis of the heavy elements.

Subject headings: nucleosynthesis — stars: abundances — stars: high-velocity — stars: late-type

I. INTRODUCTION

The study of the relative abundances of the isotopes of an element is of interest from both observational and theoretical standpoints. The observational interest is in the analysis of the molecular lines present in the spectra of cool stars and the inherently reliable results that can be obtained. The theoretical interest is in what isotopic abundances can tell us about the origin and evolution of stars.

Magnesium, which has three stable isotopes, ^{24}Mg, ^{25}Mg, and ^{26}Mg, is a good example. The reference point for studies of Mg isotopes in stars is the terrestrial-meteoritic mixture, ^{24}Mg:^{25}Mg:^{26}Mg = 79:10:11. The production of the Mg isotopes in stars will be discussed in § V. Here we note that in the nucleosynthesis of the Mg isotopes the production of the neutron-rich nuclei ^{25}Mg and ^{26}Mg depends on the abundance of heavy elements (defined to be the elements with $Z > 2$) already present in the stars at the time of their formation whereas the production of ^{24}Mg does not. In the early history of the Galaxy, when the general enrichment of heavy elements was much smaller than it is now, the production of ^{25}Mg and ^{26}Mg would have been correspondingly smaller. As a result the composition of the Galaxy would have shown an even more marked predominance of ^{24}Mg nuclei over ^{25}Mg and ^{26}Mg nuclei than it does now. Such a difference should be detectable in old unmixed stars whose composition is a relic of the composition of the early Galaxy. The interest in Mg isotope abundances in dwarfs lies in the possibility that speculations of this sort can be checked. The absorption lines of the $A\,^2\Pi$–$X\,^2\Sigma^+$ system of the MgH molecule, which are present in the spectra of late-type stars, provide the means to do this.

The A–X system of MgH is suitable for a number of reasons. It is in an accessible part of the spectrum; the lines of the (0, 0) band—which is the strongest band—extend from approximately 5000 Å to 5200 Å. In late G dwarfs and K dwarfs the lines are sufficiently strong to permit study of the ^{25}MgH and ^{26}MgH lines as well as the stronger ^{24}MgH lines. In late K dwarfs, where the lines of the (0, 0) band and other $\Delta v = 0$ sequence bands become too strong for reliable analysis, lines of the weaker (0, 1) band are available. They have the advantage that the isotopic splitting is larger so that, whereas in the (0, 0) band the different isotopic lines of MgH are only partially resolved, in the (0, 1) band they are completely separate. [The (1, 0) band, which extends from approximately 4700 to 4850 Å, is in a more crowded part of the spectrum than the (0, 1) band, which extends from approximately 5450 to 5620 Å, and as a result is far less suitable for analysis.] The fact that MgH is a hydride means that the strength of MgH lines in these stars is not very sensitive to metal abundance, a property of MgH that has been emphasized by Cottrell (1978). It means that cool stars with a large range of metal abundance can be studied. Finally, we note that all the molecular data necessary for a thorough analysis are available from recent laboratory and theoretical investigations of the $A-X$ system.

What are the opportunities for determining isotopic Mg abundances in stars? Previous investigations, which have all been via (0, 0) band lines of the MgH $A-X$ system, have been limited to red giants. Boesgaard (1968) in an analysis of K and M giants made the first identification of the ^{25}Mg and ^{26}Mg isotopes in stellar spectra. She suggested that the abundances of these isotopes may be enhanced relative to ^{24}Mg. [One dwarf—61 Cyg B—was included in her list of program stars. Its (0, 0) band MgH lines are, however, too saturated for reliable analysis.] Bell and Branch (1970) found terrestrial Mg isotope abundances in Arcturus. In a reinvestigation of Arcturus (Tomkin and Lambert 1976) we confirmed that ^{26}Mg is present in terrestrial proportions and tentatively concluded that ^{25}Mg is depleted by a factor of 2. Tomkin and Lambert (1979) found terrestrial Mg isotope abundances in the Ba star HR 774. In this paper we report an investigation of Mg isotope abundances in five G and K dwarfs. They are μ Cas, ϵ Eri, Gmb 1830, and 61 Cyg A and B. Basic information about the stars is given in Table 1.

Mu Cassiopeiae is a fairly metal-deficient subdwarf. Perrin *et al.* (1977) find that Fe is 0.9 dex less abundant than in the Sun, a result that is confirmed by analysis of the weak Fe I lines in our spectra. It is an astrometric binary with a period of 23.0 years (Worek and Beardsley 1977). The faint companion has not yet been detected spectroscopically. Our spectra show no sign of it.

Epsilon Eridani is a typical Population I star. According to van de Kamp (1974) it, too, is an astrometric binary; however, Heintz (1978) does not find the evidence for a companion very convincing. Hearnshaw (1974), in a paper on C and Fe abundances of F and G stars, asserts that ϵ Eri is a spectroscopic binary. There is nothing in the literature or in our spectra to support this statement, however.

Gmb 1830 is an extremely metal-deficient subdwarf. Tomkin and Bell (1973) found Fe to be 1.3 dex less abundant than in the Sun. The eccentricity of its galactic orbit, which is 0.78, is the largest of any star in the solar neighborhood, so both composition and kinematics indicate Gmb 1830 to be a very old star.

The well-known visual binary 61 Cygni is composed of a pair of K5 V and K7 V stars. Strohbach (1970) has analyzed high-dispersion photographic spectra of 61 Cyg A and finds that its Fe abundance is solar. Mould (1978) has analyzed infrared spectra of 61 Cyg B and finds solar abundances of Fe and Fe peak elements.

II. OBSERVATIONS

All observations were made with the McDonald Observatory 2.7 m telescope, coudé spectrograph, and a 1024-element Reticon self-scanned silicon photodiode array (Vogt, Tull, and Kelton 1978). An echelle grating was used to provide coverage of 20 Å of spectrum in each observation. Overlapping orders were excluded by narrow-band interference filters. The resolution of the spectra was 0.08 Å (four diodes in a projected slit width). The signal-to-noise ratio of the spectra was typically 100 to 1.

The spectra of ϵ Eri, μ Cas, and Gmb 1830 had a central wavelength of 5140 Å. This interval was chosen because it contains unblended (0, 0) band lines from the $A\,^2\Pi-X\,^2\Sigma$ system of MgH. It also includes weaker MgH lines from higher bands of the same sequence and weak C_2 lines belonging to the Swan system (0, 0) band. An additional echelle spectrum centered at 5090 Å, also containing (0, 0) band MgH lines, was obtained for ϵ Eri. (Both of the spectra of ϵ Eri had a resolution of 0.06 Å instead of 0.08 Å.) A spectrum of Arcturus centered at 5140 Å was used to check the purity of these spectra. The depths of strong atomic lines, which typically have residual intensities between 0.1 and 0.2 of the continuum intensity, measured off this spectrum, differed by less than 1% from the depths of the same lines in the Arcturus atlas (Griffin 1968), which has a resolution of 0.023 Å at this wavelength. This indicates that there is no significant contamination of the spectra by scattered light.

In 61 Cyg A and B, which are about 1000 K cooler than the other stars, the (0, 0) band MgH lines are

TABLE 1

PROGRAM STARS

NAME	HD	SPECTRAL TYPE	V	T_e (K)	IRON ABUNDANCE [Fe/H]	Ref.
μ Cas................	6582	G5 Vp	5.18	5300	−0.9	1, 2
ϵ Eri................	22049	K2 V	3.73	5100	−0.2	3
Gmb 1830............	103095	G8 VI	6.45	5000	−1.37	1
61 Cyg A............	201091	K5 V	5.22	4300	0.0	4
61 Cyg B............	201092	K7 V	6.03	3900	0.0	5

REFERENCES.—(1) This work. (2) Perrin *et al.* 1977. (3) Oinas 1974. (4) Strohbach 1970. (5) Mould 1978.

too strong and saturated for reliable analysis. The weaker (0, 1) and (1, 2) band MgH lines were observed instead. The spectra were centered at 5540, 5560, and 5580 Å (this last spectrum was not observed in 61 Cyg B).

Echelle spectra of Gmb 1830 with central wavelengths of 6160, 6320, and 6700 Å were also obtained in order to measure weak Na I, Mg I, and Al I lines.

III. ANALYSIS

The aim of the analysis is to estimate the relative abundances of ^{24}Mg, ^{25}Mg, and ^{26}Mg isotopes in each star from the relative strengths of its ^{24}MgH, ^{25}MgH, and ^{26}MgH lines. The isotopic splitting of the (0, 0) band MgH lines, which were analyzed in μ Cas, ϵ Eri, and Gmb 1830, is about 0.1 Å. This is insufficient to resolve the isotopic components into separate features; rather, the ^{25}MgH and ^{26}MgH lines are present as asymmetries in the profile of the stronger ^{24}MgH line. Spectrum synthesis, which is the most suitable method of analysis in this situation, was used to estimate the Mg isotope abundances from the MgH line profiles. For the (0, 1) and (1, 2) band lines, which were analyzed in 61 Cyg A and B, the isotopic splitting is larger—typically 0.4 Å—so that the lines from different isotopic forms of MgH are resolved into separate features. These lines were also analyzed by spectrum synthesis because, as a result of the large number of MgH lines, there is a lot of mutual blending.

Weak Swan system C_2 lines contaminate the (0, 0) band MgH lines, and weak α-system TiO lines contaminate the (0, 1) and (1, 2) band MgH lines. These lines have been included in the MgH spectrum synthesis. The information needed for the spectrum synthesis can be divided into model atmospheres and molecular data (dissociation energy, wavelengths, excitation energies, and line strengths) for MgH, C_2, and TiO.

a) *Model Atmospheres*

A grid of model atmospheres for cool main-sequence stars ($\log g = 4.5$) calculated by Bell (1978) was used. It covered the range 4000–5250 K with a spacing of 250 K and solar, $\frac{1}{3}$, and 1/10 solar abundances. The models were computed by the same program that Bell *et al.* (1976) used to compute their grid of red giant models.

The effective temperatures and iron abundances of the program stars are listed in Table 1. The effective temperatures are derived from red and infrared colors. The values for μ Cas and ϵ Eri are based on the Johnson *et al.* (1966) colors and the Johnson (1966) (T_e, color) calibration; the value for Gmb 1830—which is based on scans of the visible and near-infrared energy distribution (Whiteoak 1967) and red and infrared colors (Stebbins and Kron 1956; Johnson *et al.* 1966)—is from Tomkin (1973); and the values for 61 Cyg A and B are from Veeder (1974). The effective temperature of 3900 K for 61 Cyg B is in reasonable agreement with the value of 4000 K determined by Mould (1978). Each star was analyzed with the model atmosphere with the effective temperature closest to the actual effective temperature of the star. Epsilon Eridani and 61 Cygni A and B, which have solar or near-solar abundances, were represented by solar abundance models; μ Cas and Gmb 1830, which are deficient in iron by 0.9 dex and 1.37 dex, respectively, were represented by 1/10 solar metal abundance models. We note that, because the analysis of the relative abundances of the Mg isotopes is insensitive to uncertainties in the model parameters, the use of grid model atmospheres with parameters closest to the actual parameters of the stars is a valid approximation.

A microturbulence of 1 km s^{-1} was adopted for ϵ Eri and 61 Cyg A and B. Microturbulence is absent, or very small, in Gmb 1830 (Tomkin 1973) and in other subdwarfs (Aller and Greenstein 1960). For Gmb 1830 and μ Cas the microturbulence was set to zero. The MgH lines are weak or mildly saturated. For example, the strongest (0, 0) band ^{24}MgH line analyzed—a blend of $Q_1(23)$ and $R_2(11)$ lines at 5134.56 Å—has equivalent widths of 24, 57, and 32 mÅ in μ Cas, ϵ Eri, and Gmb 1830, respectively. The (0, 1) and (1, 2) band ^{24}MgH lines in 61 Cyg A and B have equivalent widths of 20–40 mÅ. The ^{25}MgH and ^{26}MgH lines are much weaker than the ^{24}MgH lines. The saturation of these lines, and therefore the isotopic abundance ratio, is not sensitive to the exact value used for the microturbulence. A check of the saturation of the ^{24}MgH lines in Gmb 1830 is discussed in § IV.

Before comparison with the observed spectra, the appropriate instrumental broadening was applied to each synthetic spectrum. In addition to the instrumental and stellar Doppler broadening, macroturbulent broadening of 2 km s^{-1}, with a Gaussian distribution, was required for the best fit of the synthetic and observed spectra of ϵ Eri. No macroturbulent broadening of the μ Cas, Gmb 1830, and 61 Cyg A and B synthetic spectra was required, indicating that any macroturbulence in these stars is less than 2 km s^{-1}.

b) *Molecular Data*

i) MgH

The dissociation energy, $D_0{}^0 = 1.33$ eV, determined by Balfour and Cartwright (1976) was adopted. Use of the slightly lower and more accurate value of 1.27 eV (Balfour and Lindgren 1978) would not cause any significant change in the synthetic spectra.

The wavelengths of the ^{24}MgH lines were taken from Balfour and Cartwright (1976). The calculated isotopic shifts of the ^{25}MgH and ^{26}MgH lines with respect to the ^{24}MgH lines were used to determine the wavelengths of the ^{25}MgH and ^{26}MgH lines. The calculated and observed wavelengths of the (0, 0) and (0, 1) band ^{25}MgH and ^{26}MgH lines, which have been measured in the laboratory (Balfour 1970), are in agreement. The excitation energies were also taken from Balfour and Cartwright.

The vibration-rotation interaction is appreciable for the A–X transition of MgH. Its effect was included by multiplying the Hönl-London factor of each line by a factor that depends on the band and rotational quantum number of the line. These factors were calculated by a modification (Lambert and Slavsky 1980) of a computer program—TRAPRB—described by Jarmain (1971). The necessary spectroscopic constants and variation of electronic transition moment with internuclear separation were taken from Balfour and Cartwright (1976) and Saxon, Kirby, and Liu (1978), respectively.

The Mg abundance for each star was set by the solar Mg abundance (Lambert and Luck 1978) and the assumption that the abundance of Mg relative to the Sun is the same as for Fe (see Table 1). For Gmb 1830 the measured Mg abundance was used. The computed strengths of the (0, 0), (1, 1), (0, 1), and (1, 2) band ^{24}MgH lines were matched to their actual strengths in each star by individual adjustment of the band oscillator strengths. The Mg abundances and band oscillator strengths do not have to be absolutely correct because the purpose of the spectrum synthesis is to determine the *relative* abundances of the different Mg isotopes from the *relative* strengths of their MgH lines.

A comparison of these band oscillator strengths with the theoretical band oscillator strengths of Kirby, Saxon, and Liu (1979) serves as a rough quantitative check of our calculations. The accuracy of the theoretical band oscillator strengths is indicated by the good agreement of the theoretical and measured (Nedelec and Dufayard 1978) radiative lifetimes of the $A\,^2\Pi\ v' = 0$ and 1 vibrational states. Two types of comparison can be made.

One is to compare the ratio of band oscillator strengths for two bands in the same sequence. In the synthetic spectra of Gmb 1830, which has unblended lines from the (1, 1) band as well as the (0, 0) band, the ratio $f_{(1,1)}/f_{(0,0)}$ was 0.97 ± 0.05. The theoretical ratio is 0.88. In the synthetic spectra of 61 Cyg A and B the ratio $f_{(1,2)}/f_{(0,1)}$ was 2.0 ± 0.1. The theoretical ratio is 1.8. We see that the synthetic spectra and theoretical band oscillator strengths pass this consistency test.

The second comparison is one of the actual band oscillator strengths. For ϵ Eri the agreement is fairly good (a synthetic spectrum $f_{(0,0)}$ of 0.11 versus the theoretical value of 0.161), while for 61 Cyg there is a difference of about a factor of 3 (a synthetic spectrum $f_{(0,1)}$ of 0.0029 for both 61 Cyg A and 61 Cyg B versus the theoretical value of 0.00861). Epsilon Eridani is most suitable for the $f_{(0,0)}$ check because its composition is roughly solar, which means that the error in its synthetic spectrum $f_{(0,0)}$ caused by abundance and model atmosphere uncertainties is minimized. Consideration of the potential errors—the use of one log g of 4.5, uncertainties of the Mg abundance, etc.—that affect the synthetic spectra band oscillator strengths suggests they are not inconsistent with the theoretical values. We also note that $f_{(0,1)}$ is much smaller than $f_{(0,0)}$, so its theoretical value is probably quite sensitive to the adopted molecular potential.

Another system of MgH with numerous bands in the visible and near-infrared is the $B'\,^2\Sigma^+$–$X\,^2\Sigma^+$ system. It has not been observed in stellar spectra. The extensive laboratory measurements of Balfour and Lindgren (1978) were used to search for lines from this system in the spectra of 61 Cyg A and B, which have the strongest MgH lines of our program stars. No lines were found. A search for lines of this system in the spectra of M dwarfs, in which MgH is even stronger than in 61 Cyg, might be successful. Such an identification would be of interest because the isotopic splitting of this system is much larger than it is for the A–X system. If lines of the B'–X system are present in M dwarf spectra, they may—because it is difficult to get high-resolution spectra of these faint stars—provide the best means of determining their Mg isotopic abundances.

ii) C_2

Weak lines from the (0, 0) and (1, 1) Swan bands interfere with the (0, 0) and (1, 1) band lines analyzed in μ Cas, ϵ Eri, and Gmb 1830. The C_2 data were the same as we used in our investigation of Mg isotopes in Arcturus (Tomkin and Lambert 1976). The strengths of the C_2 lines in the μ Cas and ϵ Eri synthetic spectra were adjusted by changing the carbon abundance so that the strength of the C_2 line at 5135.6 Å, which is a blend of (0, 0) band $P_1(45)$, $P_2(44)$, and $P_3(43)$ lines, matched the observed strength of this line in each star (see Fig. 1). The C_2 lines in Gmb 1830 are so weak that they are undetectable in our spectrum and do not significantly affect the Gmb 1830 MgH lines. The synthetic spectra of Gmb 1830, which included C_2 lines calculated with carbon 1.4 dex less abundant than in the Sun (a result Tomkin and Bell 1973 obtained from analysis of CH), are consistent with the observed upper limit on the strength of C_2 in Gmb 1830.

iii) TiO

Weak lines from the (0, 1) and (1, 2) bands of the α-system interfere with the (0, 1) and (1, 2) band MgH lines analyzed in 61 Cyg A and B. [TiO lines of the (2, 3) band, which are much weaker than the (0, 1) and (1, 2) band lines, were not included in the spectrum synthesis.] Identifications and wavelengths were taken from a comprehensive listing of TiO lines between 4000 and 9000 Å provided by Phillips (see Phillips 1973). Excitation energies were calculated with the molecular constants determined by Phillips (1973). Franck-Condon factors for the α system were taken from Collins and Faÿ (1974). The electronic oscillator strength, $f_{el} = 0.12$, was taken from Price, Sulzmann, and Penner (1974).

The strength of the TiO in the synthetic spectra of 61 Cyg B was matched to the observed strength of TiO in 61 Cyg B by adjusting the Ti abundance. Unblended (0, 1) and (1, 2) band lines in the 5540 and 5560 Å spectra were used to make the match. A

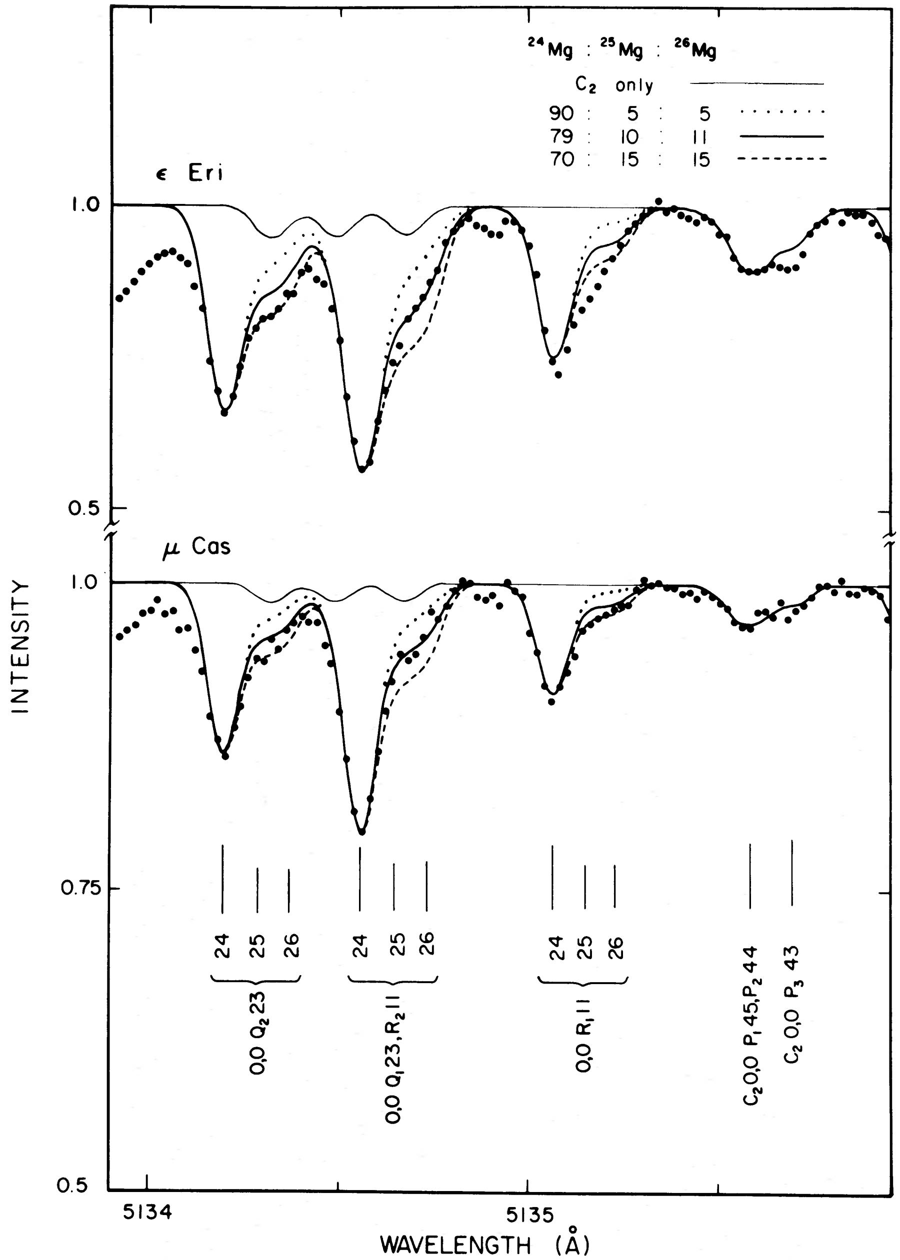

FIG. 1.—Three MgH (0, 0) band lines in ε Eri and μ Cas fitted with synthetic spectra computed for three different Mg isotope mixtures. The synthetic spectrum for C_2 lines alone is also shown. The strength of the C_2 lines is set by matching the strength of the C_2 line at 5135.6 Å.

check of the strength of α-system TiO lines in 61 Cyg B was made with an echelle Reticon spectrum centered at 5285 Å of (0, 0) band α-system lines. The Ti abundance needed for a match of the computed and observed strength of the (0, 0) band lines in this spectrum was in good agreement with the Ti abundance demanded by the (0, 1) and (1, 2) band lines.

In 61 Cyg A, which is hotter than 61 Cyg B, TiO is much weaker than in 61 Cyg B. This weakness has the advantage that it has, at most, a minor effect on the analysis of MgH in 61 Cyg A; however, because of this weakness, it is difficult to make a direct measurement of the strength of α-system TiO lines. An indirect estimate of their strength was made via the much stronger lines of the γ system. (Echelle Reticon spectra, obtained for an investigation of Ti isotopes in late-type stars by Clegg, Lambert, and Bell 1979, were used to make this estimate.)

TABLE 2

MgH LINES ANALYZED IN μ CASSIOPEIAE, ϵ ERIDANI, AND Gmb 1830

			ISOTOPIC ABUNDANCE		
LINE	ISOTOPE	λ (Å)	μ Cas	ϵ Eri	Gmb 1830
(0, 0)Q_1(30), R_1(17)............	24	5101.408	*	80	*
	25	5101.544	*	10	*
	26	5101.668	*	b	*
(0, 0)Q_1(23), R_2(11)............	24	5134.558	80	80	94
	25	5134.647	10	10	3
	26	5134.730	10	10	3
(0, 0)R_1(11)...................	24	5135.061	b	b	90
	25	5135.148	b	b	5
	26	5135.228	b	b	5
(1, 1)Q_2(15)...................	24	5136.014	b	b	94
	25	5136.076	b	b	3
	26	5136.133	b	b	3
(1, 1)Q_1(15)...................	24	5136.428	b	b	94
	25	5136.494	b	b	3
	26	5136.556	b	b	3

NOTE.—"b" is a blended line; asterisk indicates no observation.

IV. RESULTS

MgH (0, 0) band lines at 5101 and 5134 Å were analyzed in μ Cas, ϵ Eri, and Gmb 1830. These lines, which have been used in previous investigations (Tomkin and Lambert 1976, 1979), are listed in Table 2.

MgH (0, 1) and (1, 2) band lines have not previously been analyzed in stellar spectra. It is of interest to note that these lines are present in the spectrum of Arcturus (Griffin 1968). Although they are too weak—Q-branch ^{24}MgH lines have absorption depths of up to 5%—for isotopic analysis, they account for many weak lines in this part of the spectrum of Arcturus. Wavelength intervals with clean ^{25}MgH and ^{26}MgH (0, 1) and (1, 2) band lines were selected from the spectra of 61 Cyg A and B. Some lines were later rejected after comparison with the synthetic spectra showed them to be blended with weak, unidentified atomic lines. The unblended MgH lines used to

TABLE 3

MgH LINES ANALYZED IN 61 CYGNI A AND B

			ISOTOPIC ABUNDANCE	
LINE	ISOTOPE	λ (Å)	61 Cyg A	61 Cyg B
(1, 2)Q_2(7)..........	26	5539.947	10	b
	25	5540.186	10	b
	24	5540.445	80	b
(0, 1)Q_1(18).........	25	|5545.005|	10	8
(1, 2)Q_1(5)..........	26	|5545.066|	10	8
(0, 1)Q_1(18).........	24	5545.224	80	84
(1, 2)Q_1(5)..........	24	5545.571	80	84
(0, 1)R_1(8)..........	25	|5555.908|	9	10
(0, 1)Q_2(16).........	25	|5555.969|	9	10
(1, 2)P_2(18).........	26	|5555.977|	9	10
(0, 1)R_1(8)..........	24	5556.156	82	80
(0, 1)Q_2(16).........	24	5556.220	82	80
(1, 2)P_2(18).........	24	5556.507	82	80
(1, 2)P_2(16).........	26	|5560.916|	10	10
(0, 1)Q_2(15).........	26	|5560.983|	10	10
(1, 2)P_2(16).........	24	5561.466	80	80
(0, 1)Q_2(15).........	24	5561.466	80	80
(0, 1)Q_2(12).........	26	5574.791	10	*
	25	5575.055	b	*
	24	5575.342	80	*
(0, 1)Q_1(11), R_1(4)...	26	5579.300	b	*
	25	5579.568	10	*
	24	5579.857	80	*

NOTE.—Lines with wavelengths between bars are a single composite ^{25}MgH and/or ^{26}MgH feature. Asterisk indicates no observation.

estimate the isotopic abundances in 61 Cyg A and B are listed in Table 3.

For all stars synthetic spectra were calculated for three different isotopic mixtures: ^{24}Mg:^{25}Mg:^{26}Mg = 79:10:11 (terrestrial), 70:15:15, and 90:5:5. Additional synthetic spectra with ^{24}Mg:^{25}Mg:^{26}Mg = 94:3:3 and 100:0:0 were done for Gmb 1830. The isotopic abundances estimated from comparison of the synthetic and observed spectra are given in Tables 2 and 3. We now discuss the results for each star.

a) *μ Cassiopeiae*

This star, which is the hottest of the program stars, has the weakest MgH lines. The wavelength interval at 5134 Å is shown in Figure 1. It is clear from inspection of the line at 5134.6 Å that the isotopic abundances are terrestrial, or nearly so.

The other two MgH lines in Figure 1, at 5134.2 and 5135.1 Å, are affected by blending with weak atomic lines. This is more obvious in ϵ Eri than in μ Cas. The 5135.1 Å line is affected by a Y I line at 5135.18 Å (Moore, Minnaert, and Houtgast 1966; Kurucz and Peytremann 1975). The culprit that affects the 5134.2 Å line is unidentified. We note that in the synthetic spectra for all the stars only MgH and, where appropriate, C_2 or TiO lines have been included. As a result, a synthetic spectrum for a particular mixture of isotopes must be consistent not only with one or two MgH lines; it must be consistent with all MgH lines. For example, if one were unaware that the 5134.2 and 5135.1 Å MgH lines in μ Cas are affected by blends, one would suppose the ^{24}Mg:^{25}Mg:^{26}Mg abundances in μ Cas to be 70:15:15 because the synthetic spectrum computed for this mixture fits these lines best. However, the ^{24}Mg:^{25}Mg:^{26}Mg = 70:15:15 synthetic spectrum conflicts with the 5134.6 Å MgH line because it falls *below* the observed profile, and therefore we know that this cannot be the correct mixture of isotopes.

Four weak, unblended Fe I lines on the 5140 Å spectra of μ Cas and Gmb 1830 were used to determine the Fe abundance of μ Cas with respect to Gmb 1830. The lines are at 5131.476, 5143.728, 5145.102, and 5148.051 Å and have equivalent widths of 56, 12, 31, and 44 mÅ, respectively, in μ Cas and 48, 11, 26, and 28 mÅ, respectively, in Gmb 1830. Iron was found to be 0.91 dex less abundant than in the Sun (this assumed a Gmb 1830 Fe abundance of 1.37 dex less than solar, a result that will be derived when we discuss Gmb 1830). This is in good agreement with the μ Cas Fe abundance of -0.90 dex determined by Perrin *et al.* (1977). Iron abundances of -0.6 dex (Catchpole, Pagel, and Powell 1967), -0.6 dex (Cohen 1968), and -0.7 dex (Hearnshaw 1974) with respect to the Sun have been determined in earlier investigations of μ Cas.

b) *ϵ Eridani*

Figure 1 shows the wavelength interval at 5134 Å. Inspection of the line at 5134.6 Å shows that the isotopic abundances are terrestrial. As in μ Cas, the profiles of the other two MgH lines, at 5134.2 and 5135.1 Å, are affected by blends.

c) *Gmb 1830*

The spectrum of this very metal-deficient star is relatively clean so that the continuum is well defined in the wavelength region of the (0, 0) band MgH lines. Another benefit of the metal deficiency is that it affects MgH lines much less than atomic lines. As a result, there are many unblended MgH lines suitable for analysis.

The wavelength interval at 5134 Å—extended 1 Å to the red to include three (1, 1) band lines—is shown in Figure 2. All six MgH lines in the figure show that ^{25}Mg and ^{26}Mg are less abundant than they are terrestrially. The synthetic spectrum calculated with ^{24}Mg:^{25}Mg:^{26}Mg = 94:3:3 best fits the observed spectrum, and we adopt this as the best estimate of the Mg isotope abundances. The estimated uncertainty in this result is $(+4, -3)$ for ^{25}Mg and ± 2 for ^{26}Mg. The uncertainty in the abundance for ^{25}Mg is larger than it is for ^{26}Mg because the ^{25}MgH lines are not as well separated from the ^{24}MgH lines as the ^{26}MgH lines are. The main source of uncertainty is the noise of the data.

The ^{25}MgH and ^{26}MgH lines are so weak that it is reasonable to ask if they have even been detected. The profiles of the MgH lines in Figure 2 and the other MgH lines in the spectrum do show, on average, a red asymmetry, so we can be fairly sure that ^{26}MgH lines are present. Because we cannot be sure that ^{25}MgH lines are present, the possibility that ^{25}Mg is absent, or extremely underabundant, cannot be ruled out. We now discuss two circumstances—poor data and serious misjudgment of the saturation of the ^{24}MgH lines—that might conceivably affect the analysis.

Could the observed spectrum be distorted by some unsuspected instrumental error or error of observation? We think that this is very unlikely because (i) two spectra, observed on two separate occasions, are in excellent agreement; (ii) as discussed in § II, a check with the spectrum of Arcturus showed that the spectra are not affected by scattered light; and (iii) the resolution of four channels, determined from spectra of Fe/Ne arcs observed immediately after each stellar observation, is what is expected.

The microturbulence adopted for the calculation of the Gmb 1830 synthetic spectra was zero. If, for a moment, we suppose that the actual microturbulence of Gmb 1830 is very large, then the saturation of the ^{24}MgH lines will be less. The net effect of this will be to increase the abundances of ^{25}Mg and ^{26}Mg relative to ^{24}Mg. The microturbulence needed for a significant effect is large; the use of a microturbulence of 1 km s^{-1} instead of zero, for example, will not cause a significant change in the results. Two lines of evidence, in addition to that discussed in § III, indicate that Gmb 1830 does not have a large microturbulence. First, the narrow absorption lines in the spectrum of Gmb

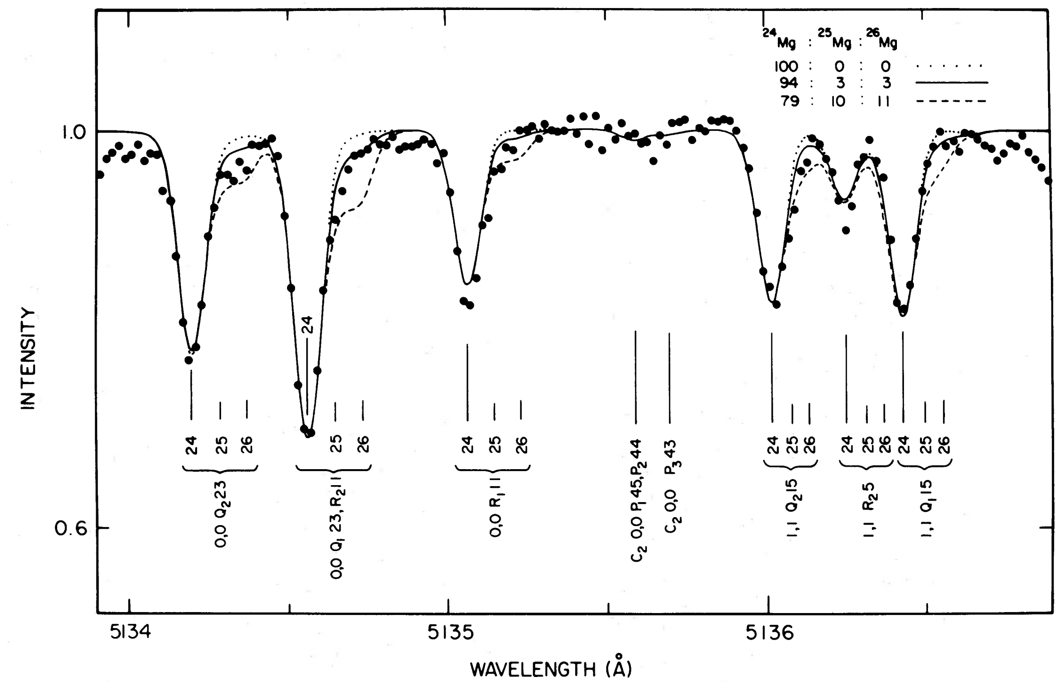

FIG. 2.—MgH (0, 0) and (1, 1) band lines in Gmb 1830 fitted with synthetic spectra computed for three different Mg isotope mixtures. The ^{25}MgH and ^{26}MgH lines are much weaker than in the synthetic spectrum computed with a terrestrial mixture (^{24}Mg:^{25}Mg:^{26}Mg = 79:10:11). The synthetic spectrum computed with ^{24}Mg:^{25}Mg:^{26}Mg = 94:3:3 fits the data best. The C_2 lines are so weak that they have no significant effect on the profiles of the MgH lines.

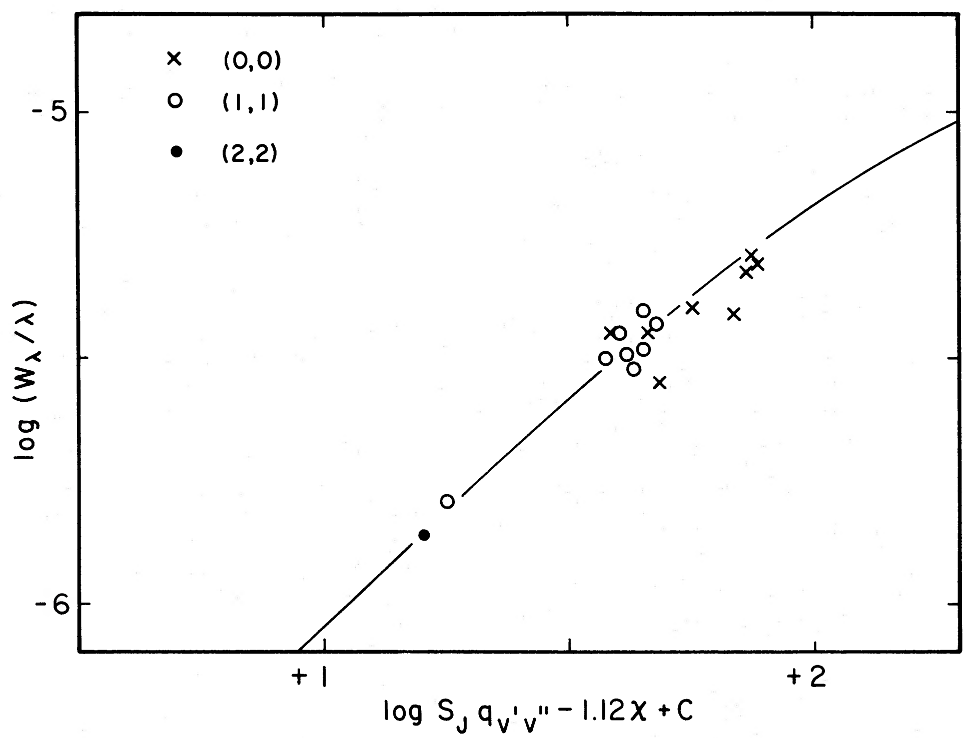

FIG. 3.—MgH curve of growth in Gmb 1830 fitted with a curve of growth computed for MgH and no microturbulence

1830 leave no room for a microturbulence of more than 2 km s^{-1} (or, for that matter, for any other form of turbulent broadening). Second, the microturbulence was estimated from the MgH curve of growth shown in Figure 3. Unblended (0, 0), (1, 1), and (2, 2) band lines, with equivalent widths between 8 and 30 mÅ, were measured on the 5140 Å spectrum. The curve of growth is best fitted by a theoretical MgH curve of growth calculated with a microturbulence of zero. We conclude that the microturbulence is indeed zero, or nearly zero, and that the calculated saturation of the ^{24}MgH lines is not in serious error.

In order to follow up the detection of nonterrestrial Mg isotope abundances, Na, Mg, and Al abundances were determined from observations of weak atomic lines. (Na and Al are the elements that bracket Mg.) The equivalent widths of the Na I (6154.23 and 6160.75 Å), Mg I (6318.71 and 6319.24 Å), and Al I (6696.03 Å) lines are listed in Table 4. (The second Al I line, at 6698.67 Å, is present in the Reticon spectrum. It has not been used because its profile is distorted by an unidentified blend, or glitch, in the data.) Weak lines of Ca I, V I, and Fe I were also present on these Reticon spectra and were used to determine the abundances of these elements. Solar oscillator strengths were used to determine differential abundances with respect to the Sun. The solar oscillator strength of each line was calculated with the aid of the solar equivalent width measured off the solar atlas of Delbouille, Neven, and Roland (1973), the Holweger and Müller (1974) solar model atmosphere, a solar microturbulence of 1.0 km s^{-1}, and a solar abundance of each element taken from Ross and Aller (1976). A check of the Fe I line solar oscillator strengths with the laboratory measurements of May, Richter, and Wichelmann (1974) showed excellent agreement. The -1.0 dex metal abundance model atmosphere was used for Gmb 1830. It was the most metal-deficient model available. The main electron donors (Mg, Si, and Fe) are, on average, about 0.3 dex more deficient than this in Gmb 1830, so a reanalysis was done with a -0.5 dex model to check how the calculated abundances depend on model metal abundance. This reanalysis showed that use of a more metal-deficient model would not have altered the abundances significantly.

The abundances are given in Table 4. Na is much more deficient than Mg, while Al is marginally more deficient than Mg. Iron is 1.37 dex less abundant than in the Sun, a result that confirms the value of -1.3 dex obtained by Tomkin and Bell (1973).

d) *61 Cygni A and B*

These two stars, which are approximately 1000 K cooler than the other program stars, have such strong MgH that the (0, 0) band lines are too saturated for reliable analysis. The weaker (0, 1) and (1, 2) band lines have been analyzed instead. An advantage of working with these lines is that the isotopic splitting is sufficient to completely resolve the ^{24}MgH, ^{25}MgH, and ^{26}MgH lines into individual features.

Two (0, 1) band lines in 61 Cyg A are shown in Figure 4. Comparison of the ^{26}MgH $Q_2(12)$ line and the ^{25}MgH $Q_1(11)$ line with the synthetic spectra shows that the abundances of the Mg isotopes in 61 Cyg A are terrestrial, or nearly so. [The ^{25}MgH $Q_2(12)$ line is blended with an unidentified line, while the ^{26}MgH $Q_1(11)$ line is blended with ^{24}MgH $Q_2(11)$. Neither line is suitable for estimating isotopic abundances.] Additional ^{25}MgH and ^{26}MgH lines in 61 Cyg A and B are shown in Figures 5 and 6. They confirm that 61 Cyg A has terrestrial isotope abundances and show that 61 Cyg B does too.

The three main factors that determine the accuracy of the analysis are the finite signal-to-noise ratio of the data, the continuum definition, and the presence of weak, unidentified blends. We end this section with a discussion of their effect.

The signal-to-noise ratio of the data affects the definition of the weak ^{25}MgH and ^{26}MgH lines. In

TABLE 4

ATOMIC LINES IN Gmb 1830

Line	λ (Å)	Equivalent Width (mÅ)	χ (eV)	*gf*	Abundance (dex relative to Sun)	
Na I	6154.23	3.1	2.10	3.1×10^{-2}	−1.74	−1.80
Na I	6160.75	5.0	2.10	6.5×10^{-2}	−1.85	
Mg I	6318.71	7.5	5.11	1.1×10^{-2}	−1.26	−1.25
Mg I	6319.24	4.1	5.11	5.5×10^{-3}	−1.24	
Al I	6696.03	5.3	3.14	2.7×10^{-2}	−1.43	−1.43
Ca I	6161.29	30.4	2.52	7.4×10^{-2}	−1.31	−1.24
Ca I	6163.75	33.1	2.52	6.8×10^{-2}	−1.21	
Ca I	6166.44	39.9	2.52	9.0×10^{-2}	−1.21	
V I	6150.15	7.7	0.30	3.4×10^{-2}	−1.36	−1.36
Fe I	6151.62	17.6	2.18	5.5×10^{-4}	−1.53	−1.37
Fe I	6157.73	21.0	4.07	6.7×10^{-2}	−1.39	
Fe I	6165.36	10.8	4.14	3.3×10^{-2}	−1.38	
Fe I	6705.11	10.0	4.61	1.0×10^{-1}	−1.39	
Fe I	6710.32	4.6	1.48	1.7×10^{-5}	−1.55	
Fe I	6713.04	3.8	4.61	3.3×10^{-2}	−1.37	
Fe I	6713.75	5.6	4.79	4.3×10^{-2}	−1.10	
Fe I	6715.39	5.1	4.61	3.7×10^{-2}	−1.28	

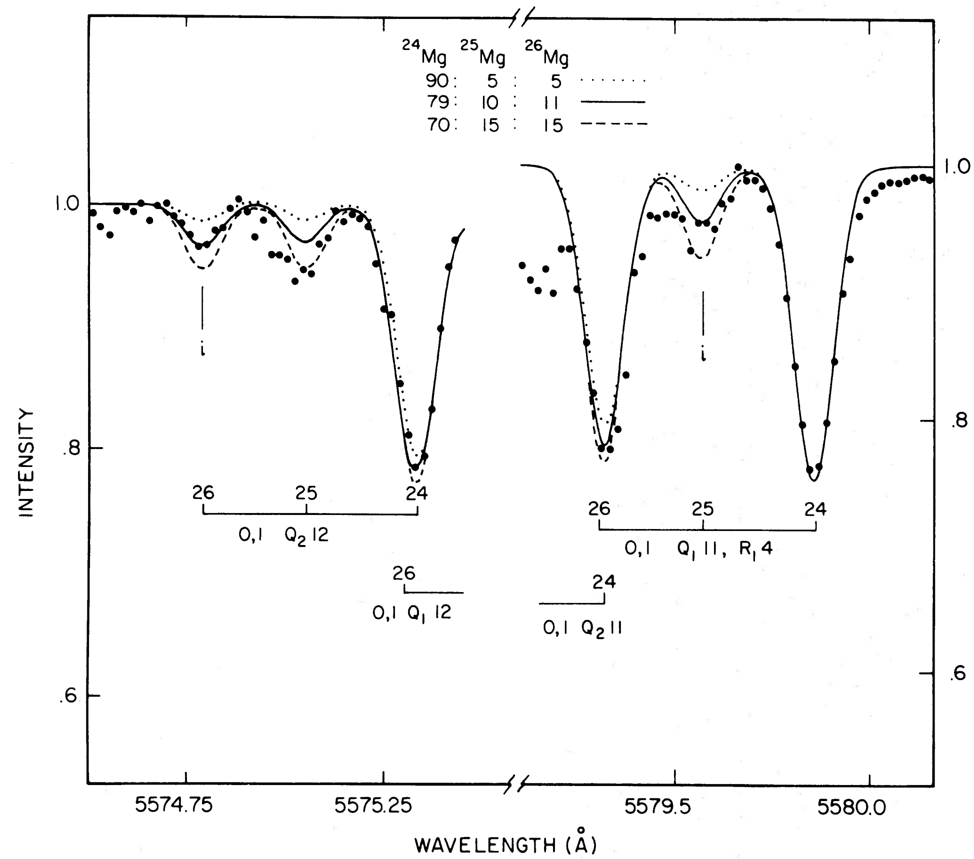

FIG. 4.—The MgH (0, 1)$Q_2(12)$ and $Q_1(11)$ lines in 61 Cyg A fitted with synthetic spectra computed for three mixtures of the Mg isotopes. The ^{26}MgH $Q_2(12)$ line and the ^{25}MgH $Q_1(11)$ line (each marked "i") are both best fitted by the synthetic spectrum computed for a terrestrial isotopic mixture. The blue side of the ^{25}MgH $Q_1(11)$ line is influenced by a weak line, and the ^{25}MgH $Q_2(12)$ line is blended with a weak line. No attempt has been made to include either of these unidentified lines in the synthetic spectra. The continuum level of the spectrum on the left is depressed by the wing of an Fe I line at 5572.9 Å. The continuum level of the spectrum on the right is reliably defined by continuum windows on both sides of the piece of spectrum shown.

some stars it is this consideration alone that governs the accuracy of the results. The very weak ^{25}MgH and ^{26}MgH lines of Gmb 1830, for example, would benefit from data with an improved signal-to-noise ratio. It is expected that new instrumentation, which will be available in the near future, will provide better data.

In all of the program stars except 61 Cyg B, the continuum definition is set mainly by the signal-to-noise ratio of the data. Uncertainty in this area will also be reduced by use of improved data. In 61 Cyg B, which has the most crowded spectrum of the program stars, the continuum definition is set by the availability of continuum, or near-continuum, points. For this star there is only limited scope for improving the continuum definition by using data of better signal-to-noise ratio. We note that, with the help of the 61 Cyg A spectra, a useful check of the continuum placement in the 61 Cyg B spectra was possible. The check was made by overlaying pairs of 61 Cyg A and B spectra at the same wavelength to see that the envelope of continuum points in the 61 Cyg B spectrum was consistent with the continuum level in the 61 Cyg A spectrum.

Many MgH lines are blended with weak lines that cannot be identified in either the solar line list (Moore, Minnaert, and Houtgast 1966) or the Kurucz and Peytremann (1975) line list. The 61 Cyg A and B spectra are most affected by this source of uncertainty. The problem has been solved largely by choice of ^{25}MgH and ^{26}MgH lines that have clean profiles and provide consistent results. However, we note that even for these lines—identified by an "i" in Figures 4, 5, and 6—the fit with the synthetic spectra is by no means perfect in all cases. In some of these cases the imperfect fit is due to very weak, unidentified blends as well as the noise of the data.

V. DISCUSSION

We have found that in all of the program stars except Gmb 1830, the abundances of the Mg isotopes are terrestrial. In Gmb 1830, in which ^{24}Mg:^{25}Mg:^{26}Mg = 94:3:3, the isotope abundances are distinctly

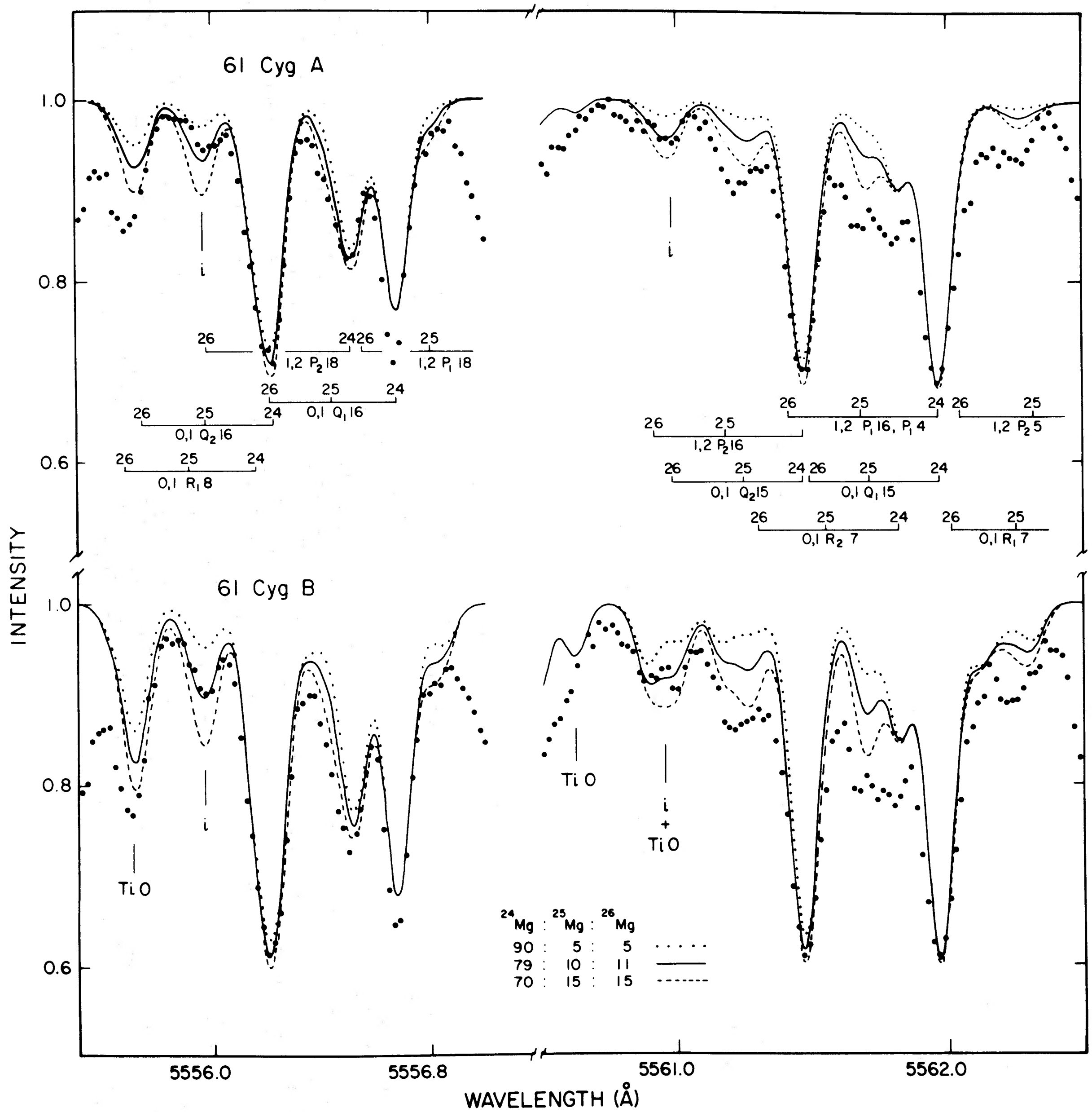

FIG. 5.—Two wavelength intervals with (0, 1) and (1, 2) band MgH lines in 61 Cyg A and B. The clean ^{25}MgH and ^{26}MgH features are labeled "i." The feature at 5556 Å is a blend of two ^{25}MgH lines and a ^{26}MgH line. The feature at 5561 Å is a blend of two ^{26}MgH lines. In both 61 Cyg A and B both features are best fitted by the synthetic spectrum computed for terrestrial isotope abundances.

nonterrestrial. Relative to the α-particle nucleus ^{24}Mg, the neutron-rich isotopes ^{25}Mg and ^{26}Mg are much less abundant than they are terrestrially. Na and Al are 0.6 ± 0.1 dex and 0.2 ± 0.1 dex, respectively, less abundant relative to Mg in Gmb 1830 than they are in the Sun. Na and Al each have only one stable isotope—^{23}Na and ^{27}Al—so that these are also the abundances of ^{23}Na and ^{27}Al relative to ^{24}Mg. Evidently the neutron-rich nuclei ^{23}Na and ^{27}Al are also underabundant relative to ^{24}Mg. To interpret these results, we must consider how Mg is synthesized in stars.

Of the variety of possible sites of Mg isotope production there are three that appear to be the most important. In massive stars (Lamb *et al.* 1977; Arnett and Wefel 1978) ^{25}Mg and ^{26}Mg are produced during hydrostatic He burning by ^{22}Ne$(\alpha, n)^{25}$Mg and subsequent conversion of some ^{25}Mg into ^{26}Mg by neutron capture while ^{24}Mg is produced during hydrostatic C burning; the main reaction sequence is

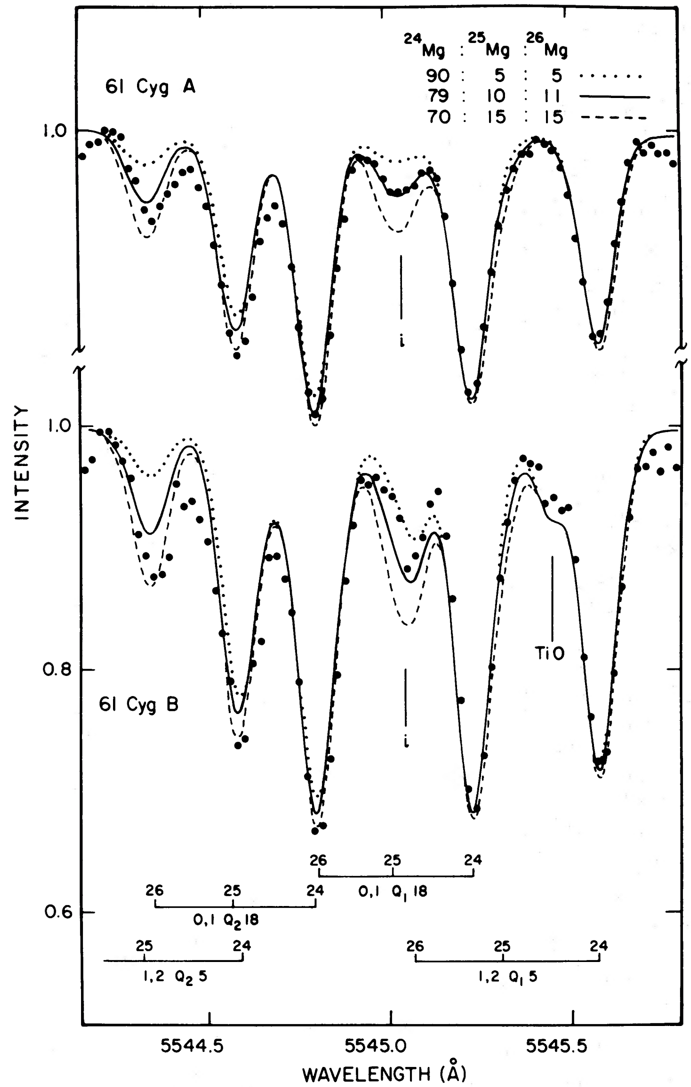

FIG. 6.—MgH (0, 1) and (1, 2) band lines in 61 Cyg A and B. A clean MgH feature, which is a blend of a ^{25}MgH line and a ^{26}MgH line, is labeled "i." In 61 Cyg A the synthetic spectrum calculated with terrestrial isotope abundances fits the feature best. In 61 Cyg B the synthetic spectrum calculated with terrestrial isotope abundances is slightly stronger than the observed feature. This is probably an indication more of the uncertainty of the continuum level in 61 Cyg B than of a deficiency of ^{25}Mg and/or ^{26}Mg.

^{12}C(^{12}C, α)^{20}Ne(α, γ)^{24}Mg. Explosive carbon burning in intermediate-mass stars (Arnett 1969) produces all three Mg isotopes. In the convective shells of thermally pulsing stars the ^{22}Ne(α, n)^{25}Mg reaction and subsequent conversion of some ^{25}Mg to ^{26}Mg by neutron capture produces ^{25}Mg and ^{26}Mg (Truran and Iben 1977). A common feature of these sources of Mg is that the production of the neutron-rich ^{25}Mg and ^{26}Mg nuclei depends on the initial abundance of heavy elements whereas the production of ^{24}Mg is virtually independent of the initial abundance of heavy elements. (Production of ^{25}Mg and ^{26}Mg during hydrostatic C burning in massive stars may be an exception. There is time for β decay to build up the abundances of some neutron-rich nuclei. A preliminary calculation by Arnett and Wefel 1978 shows that if extreme Population II abundances are used as input, the neutron excess approaches the Population I value. The nuclei responsible for the neutron excess are not specified, so it is not possible to tell whether the production of ^{25}Mg and ^{26}Mg is significant. A detailed calculation is needed.) This means that in the early history of the Galaxy when the general enrichment of heavy elements was much smaller than it is now the production of ^{25}Mg and ^{26}Mg would have been correspondingly smaller. As a result, the abundances of ^{25}Mg and ^{26}Mg relative to ^{24}Mg would have been smaller than they are now. The same is probably true of the abundances of ^{23}Na and ^{27}Al relative to ^{24}Mg because these are also neutron-rich nuclei and would have been produced in a similar environment to that in which ^{25}Mg and ^{26}Mg were produced. The observed underabundances of ^{23}Na, ^{25}Mg, ^{26}Mg, and ^{27}Al relative to ^{24}Mg in Gmb 1830, which is a very old star, are in agreement with these expectations. In other words, the abundances of Gmb 1830 are observational evidence in qualitative support of stellar nucleosynthesis of the heavy elements.

We note that there are major theoretical uncertainties that affect any quantitative comparison of predicted and observed abundances of old, metal-deficient stars. The fraction of material ejected in the supernova of a massive star is highly uncertain. The extent of nuclear processing that takes place during the ejection event itself is also uncertain. In the case of the carbon shell of a 30–40 $M_\odot$ star, Arnett and Wefel estimate that less than 10% of the shell is subject to explosive nucleosynthesis during a supernova.

The results for Gmb 1830 should not be overemphasized because the history of heavy-element enrichment of the Galaxy is not so simple that it can be learned from the composition of one star alone. There are other old, metal-deficient stars whose abundances do not show the same pattern as Gmb 1830. An example is HD 128279, in which Spite and Spite (1977) find that the deficiencies of Na and Mg are the *same* (-1.90 dex with respect to the Sun).

What is the scope for future work? Reliable abundances for more nuclei are needed in order to map the abundance variations in more detail. Results for more stars are needed in order to investigate how the departures of the abundances from the solar abundance distribution depend on such variables as overall metal deficiency or kinematic properties. The examples of μ Cas and Gmb 1830, which have terrestrial and nonterrestrial Mg isotope abundances, respectively, and Fe deficiencies of 0.9 dex and 1.37 dex, respectively, show that the relation has a large dispersion and/or is nonlinear. Perhaps the under-abundances of ^{25}Mg and ^{26}Mg relative to ^{24}Mg set in only below a certain metal abundance.

We note that in many scenarios for element production in intermediate- and high-mass stars the neutron excess is fixed by the abundance of ^{18}O produced by cycling of the CNO nuclei into ^{14}N and subsequent conversion of ^{14}N into ^{18}O by ^{14}N$(\alpha, \gamma)^{18}$F$(\beta^+\gamma)^{18}$O. The neutron excess is thus set by the initial CNO abundances and—insofar as O is more abundant than C and N—it is dependent mainly on the initial O abundance. This suggests that for the lighter elements such as Mg, it will be more instructive to see how the deviations from the solar abundance distribution depend on oxygen abundance rather than iron abundance. The distinction is important because Sneden, Lambert, and Whitaker (1979) have found that in metal-deficient main-sequence stars the deficiency of oxygen is systematically less than the deficiency of iron.

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D. L. LAMBERT and J. TOMKIN: Department of Astronomy, University of Texas, Austin, TX 78712